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TROMBE WALL vs DIRECT GAIN: A COMPARATIVE ANALYSIS OF PASSIVE SOLAR HEATING SYSTEMS*

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ABSTRACT

Until recently only the thermal storage wall passive solar heating system had been characterized by thermal network calculators using hour-by-hour historical weather data. The greater popularity and market acceptability of direct gain systems has led to a lively, but inconclusive debate concerning the relative effectiveness of the two configurations. The recent development and validation of PASOLE/SUNSPOT, a thermal network code for direct gain enclosures, has provided the tool necessary for a quantitative comparison.

The results of performance analysis calculations for both Trombe wall and direct gain systems in Albuquerque, New Mexico, and Madison, Wisconsin, are reported in this paper. The comparative analysis includes parametric variation of fundamental design parameters including building load, glazing area, total mass, mass thickness, number of glazings, night insulation value and allowable temperature swing. Thermal comfort within the two generic types of buildings is considered as well as energy efficient performance.

1. INTRODUCTION

The thermal performance calculations presented herein for thermal storage wall and direct gain passive solar heating systems were performed with the PASOLE and SUNSPOT thermal network codes respectively. PASOLE was developed and validated a couple of years ago at Los Alamos Scientific Laboratory and has recently been documented.[1,2] SUNSPOT is a recent development.[3] It is a modified version of PASOLE capable of simulating the thermal performance of direct gain buildings on two distinct levels of detail. Level I, on which this report is based, is a fairly coarse model that considers only the gross characteristics of direct gain buildings. Nevertheless, the Level I model accurately reproduces passive test cell data at Los Alamos indicating that the dominant physical phenomena occurring in direct gain enclosures have been correctly identified and modeled. The Level II model, which is currently under development, is very detailed and, therefore, suitable for studying second order effects, which arise due to internal distribution of energy and variations in geometry and configuration.

Albuquerque, New Mexico, and Madison, Wisconsin, were selected as sites for the comparative parametric evaluation of direct gain and Trombe wall buildings because they represent environmental extremes, which, therefore, yield an appreciation of the effect of climate on appropriate passive solar design procedures. Albuquerque has a moderately high heating load, 4253 annual degree days, and is blessed with enough solar radiation, 680,000 Btu/ft^2 annually, to meet most space heating requirements fairly easily. This is an ideal climate for passive solar applications. Madison, on the other hand, has a very high heating load, 7350 annual degree days, and receives only about 518,000 Btu/ft^2 of solar radiation each year. The high heating load combined with low solar input makes passive solar design in Madison a challenging proposition.

The significance of variations in solar aperture area, number of glazings, resistance of night insulation, allowable indoor temperature swing, and building loss coefficient with respect to thermal performance of passive solar buildings is investigated on the basis of a series of SUNSPOT and PASOLE calculations. The relationship between performance and available thermal storage mass is also considered. For Trombe walls the mass wall surface area is assumed equal to the glazing area so that the storage mass is directly proportional to wall thickness. For direct gain buildings an additional degree of freedom exists because the storage mass surface area is variable as well as the thickness.

Thermal performance results are expressed in terms of the annual solar fraction. Minimum indoor air temperatures are maintained by auxiliary heaters and ventilation cooling is employed to limit the maximum air temperature to

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a specified level. The reference indoor temperature is set at 68°F in all calculations and variations, ΔT, of ±2°F, ±5°F and ±10°F about the reference value are considered. Thus, in all cases the indoor air temperature is allowed to fluctuate within prescribed bounds. However, the mean radiant temperature, which is determined by the temperatures of all surfaces bounding the living space, is constrained only by the characteristics of a specific passive design and the local weather. The thermal comfort of building occupants depends on both the mean radiant and the air temperatures in a manner which will be explained in a later section. Passive solar heated buildings, therefore, have different comfort characteristics even though the air temperature variations within the structure may be carefully bounded. In an effort to reveal general thermal comfort characteristics of different passive solar designs, monthly air, mass surface and mean radiant temperature histograms were calculated during the thermal network simulations. Appropriate weighting of the air and mean radiant temperatures yields a single thermal index, which can be directly related to occupant comfort, thereby facilitating comparative analysis.

The economic consequences of the thermal performance characteristics of passive solar heating designs considered in this paper have been evaluated by Scott Noll of Group S-2 at Los Alamos Scientific Laboratory and are reported in a separate paper in these proceedings.[4]

2. DIRECT GAIN PERFORMANCE

Since the performance characteristics of thermal storage walls have been reported extensively in the literature, some simulation results for direct gain buildings in Albuquerque are included here before proceeding to a comparative analysis of the two generic types of passive solar buildings.

2.1. Effect of Design Option Combinations

The percent solar yielded by various combinations of design options for direct gain buildings in Albuquerque is presented in Fig. 1. In each case, the thermal storage mass consists of a 6 in. thick layer of high density concrete (150 lb/ft³) with a surface area equal to three times the glazing area. Thus, the total thermal storage mass, M/A_g, is 225 lbs per square foot of glazing. Additionally, the glazing area to building load ratio, A_g/L, is 1.0 ft²/(Btu/hr°F) for each case represented in Fig. 1. The variable design options are the number of glazings, NGL, the resistance of movable night insulation, R_n, and the allowable indoor temperature swing, ΔT, about the 68°F reference value.

One of the more striking features of the bar graph in Fig. 1 is the lack of significant performance variations among configurations No. 4

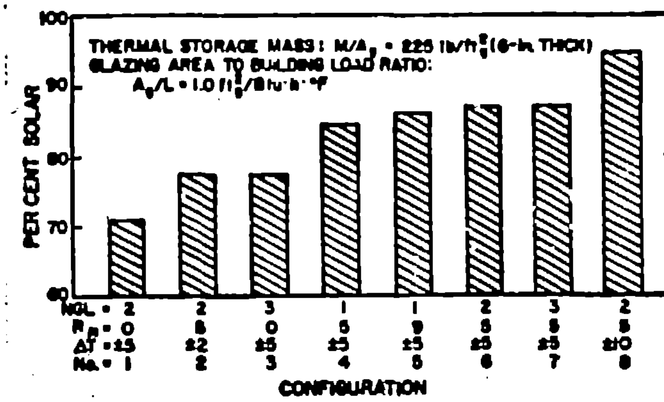

Fig. 1. The effect of design option combinations on direct gain performance in Albuquerque.

through No. 7. All four cases have a temperature swing of ±5°F. The performance appears to be dominated by the fact that each of these configurations has night insulation with a resistance of at least R5. Increasing the night insulation to R9 has little effect. Also, the effect of varying the number of glazings from one to three is largely masked by the presence of night insulation. A comparison of configurations No. 1 and No. 3 shows that, in the absence of night insulation, the number of glazings has a significant effect on performance. The allowable indoor temperature swing has a large effect on performance, even with night insulation, as indicated by a comparison of configurations No. 2, No. 6, and No. 10 for which ΔT is ±2°F, ±5°F and ±10°F respectively.

The effect of varying the glazing area to building load ratio is depicted in Fig. 2, where the behavior of four separate design option combinations is included. Cutting the glazing area in half (or doubling the thermal load) such that A_g/L is decreased from 1.0 to 0.5 causes a 20 to 25 per cent reduction in solar fraction. The rate at which solar fraction increases with the area/load ratio diminishes rapidly at high solar fractions.

3. Comparison of Direct Gain and Trombe Wall Performance in Albuquerque, New Mexico.

For the comparisons presented in this section, the number of glazings is fixed at 2, the temperature swing at ±5°F and the area/load ratio at 1.0 ft²/(Btu/hr°F). The performance of Trombe wall and Direct Gain buildings having no night insulation is plotted as a function of thermal storage mass per unit glazing area, M/A_g, in Fig. 3. The thermal storage mass is high density (150 lbs/ft³) concrete. For the Trombe wall case, the mass surface area is equal to the glazing area so that M/A_g is directly proportional to thickness of the wall. In direct gain buildings the mass surface area is variable, providing an additional degree of freedom. We have chosen to present the direct gain results in the form of three curves, each representing a different mass thickness, for which the mass per unit glazing area is then directly proportional to mass surface area. The thicknesses selected are 4 in., 6 in. and 8 in., and in each case the surface area is varied from twice the glazing area to five times the glazing area.

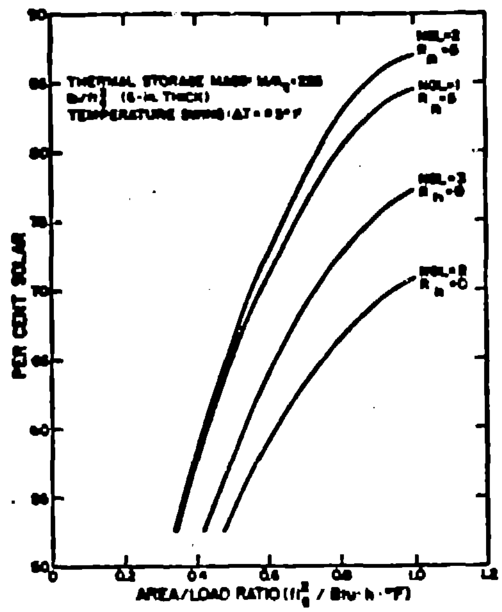

Fig. 2. Dependence of direct gain performance on the area/load ratio.

Inspection of Fig. 3 reveals a performance maximum for Trombe walls at M/A_g 175 lbs/ft_g^2, which corresponds to a thickness of 14 inches. For direct gain buildings performance maxima do not appear. Regardless of the mass thickness selected, the solar fraction continues to increase as the mass surface area is extended up to five times the glazing area. It is apparent from the curves in Fig. 3 that the best way to distribute a given amount of thermal storage mass in a direct gain building is in a thin layer (down to a minimum of 4 in.) having the largest possible surface area. When compared with a Trombe wall, the 4 in. direct gain system is capable of achieving higher solar fractions for thermal storage masses greater than 190 lbs/ft_g^2. For masses less than 190 lbs/ft_g^2 the Trombe wall is a superior performer. Thus, Trombe walls up to 15 in. thick yield higher solar fractions than direct gain buildings employing comparable amounts of thermal storage mass in a 4 in. thick layer.

In Fig. 4 we show the effect of adding R5 night insulation to the same passive solar designs represented in Fig. 3. Energy efficient performance is uniformly improved, and there is little or no change in the relative advantages of Trombe wall and direct gain buildings.

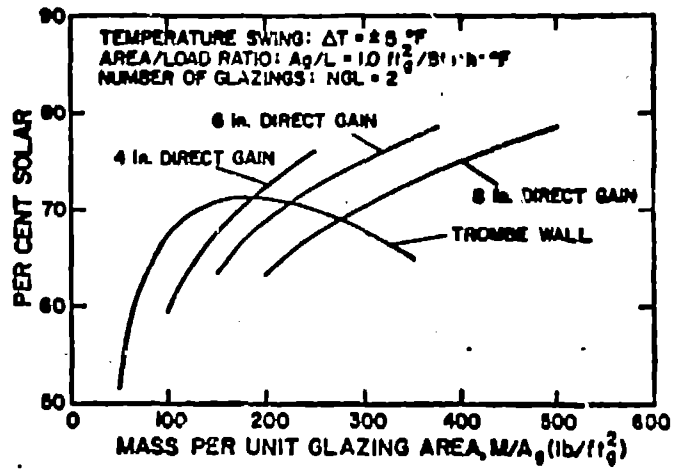

Fig. 3. Effect of thermal storage mass on passive solar building performance in Albuquerque without night insulation.

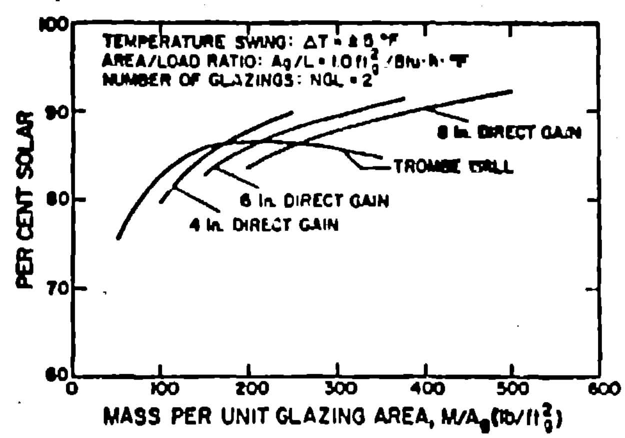

Fig. 4. Effect of thermal storage mass on passive solar building performance in Albuquerque with R5 night insulation.

4. Comparison of Direct Gain and Trombe Wall Performance in Madison, Wisconsin.

Now suppose we take the passive solar designs considered in the previous section and move them from Albuquerque, New Mexico, to the less forgiving climate of Madison, Wisconsin. The results for buildings with no night insulation are presented in Fig. 5. Note the marked deterioration of direct gain performance relative to the Trombe wall. In the harsh Madison climate a direct gain structure loses too much thermal energy through the glazing aperture to remain competitive with a Trombe wall in the absence of night insulation. However, as illustrated in Fig. 6, when R5 night insulation is added to both generic types, we obtain roughly the same relative performance previously observed in Albuquerque.

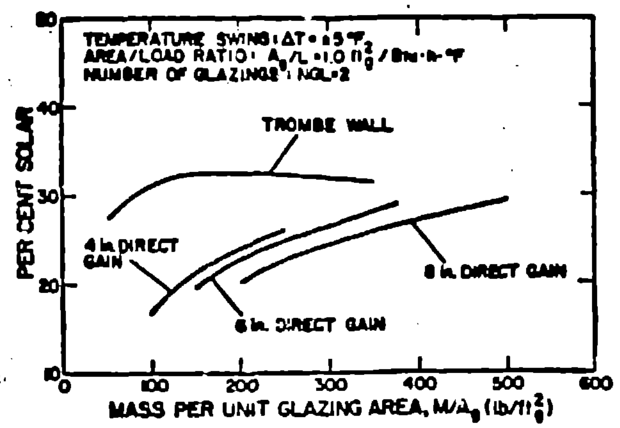

Fig. 5. Effect of thermal storage mass on passive solar building performance in Madison without night insulation.

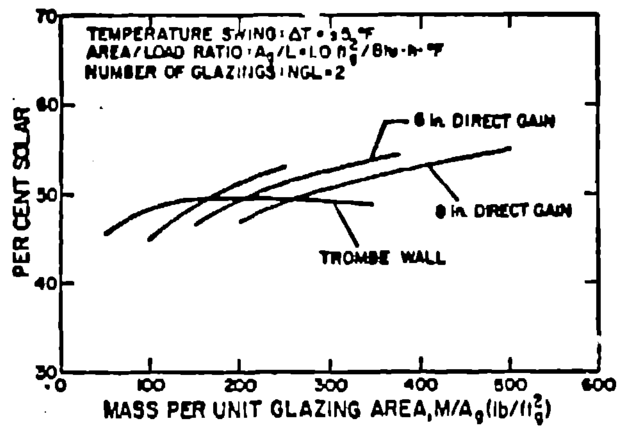

Fig. 6. Effect of thermal storage mass on passive solar building performance in Madison with R5 night insulation.

5. Mixed Systems.

Almost all buildings must have windows, for reasons of aesthetics, natural daylighting, and to serve as emergency exits. Typical window areas are in the range of 10% to 20% of the building floor area. Ten percent is a normal minimum specified by code, and architects frequently employ 20% or even more. Thus it is appropriate to use these windows as direct gain solar collection elements as much as possible, locating them on the south side of the building.

An effective design strategy is to mix direct gain and Trombe wall in the same building. A normal procedure in a cold climate is to size the window area based on the non-solar considerations mentioned above but locate them on the south side and in clerestories as much as possible. Additional solar gain is then added using Trombe walls between the south windows or by piercing the Trombe wall with a window. This approach has superior comfort and performance characteristics to the use of a pure direct gain or Trombe wall approach. It is better than the pure Trombe wall because energy-losing windows would then have to be located in the non-south walls. It is better than a pure direct gain building because the timing of energy delivery is more uniform, there is much less of a sudden drop in mean radiant temperature at nightfall, and the large temperature swing associated with a large-area direct gain building is avoided.

Simulatons of mixed systems will be made in the future to explore their performance and comfort characteristics in detail.

6. Thermal Comfort in Passive Solar Heated Buildings.

6.1. Theoretical Considerations

Most buildings of conventional construction are light weight and have limited glazing areas. As a general rule the thermal environment in such buildings is very nearly uniform. In this context the term "uniform" refers to an environment in which the air and mean radiant temperature are equal. In passive solar heated buildings the presence of massive thermal storage elements and/or large glazed areas, which communicate directly with the living space produces thermal environments which are characteristically non-uniform. The thermal storage mass surfaces facing the living space may be either warmer or colder than the room air, depending on whether current space heating requirements are being met by heat transfer from the storage mass or from the auxiliary heater. Since the mean radiant temperature is affected by radiation exchanges with all surfaces bounding an enclosure, the presence of thermal storage mass with surface temperatures different from the air temperature induces thermal non-uniformity. Large glazed areas, which communicate directly with the living space, as in direct gain buildings, can affect the mean radiant temperature in two ways. First, during daylight hours sunlight transmitted through the glazing can directly induce significant increases in the mean radiant temperature. Secondly, at night glazed areas not covered with movable insulation become much colder than the room air and tend to force the mean radiant temperature downward.

The problem of assessing thermal comfort in both uniform and non-uniform environments has been extensively researched by P. O. Fanger. On the basis of Fanger's work, it is possible to derive an expression for the "equivalent uniform temperature," T_{eu}, which is defined as "the uniform temperature of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment."[6] The details of the derivation are presented in Reference 6, which is currently under review for publication as a Los Alamos

Scientific Laboratory Report. The relationship between the equivalent uniform temperature, the air temperature, T_a, and the mean radiant temperature, T_{mr}, has the following functional form:

$$T_{eu} = f\,T_a + (1-f)T_{mr} \qquad (1)$$

$$f = f(A,C,H,V)$$

where A is the activity level (metabolic rate), C is the clothing insulation value, H is the relative humidity, and V is the relative wind velocity. Thus, the relative importance of air and mean radiant temperature depends on a set of environmental and physiological parameters. It is demonstrated in Reference 6 that for extreme, but still realistic combinations of these parameters, the function f can vary from 0.48 to 0.68. On the basis of assumptions concerning conditions likely to exist in a passive solar heated dwelling, the following expression for the equivalent uniform temperature is obtained.

$$T_{eu} = 0.55\,T_a + 0.45\,T_{mr} \qquad (2)$$

Eq. 2 represents a subject dressed in medium-weight clothing and performing light activity in an environment with a relative humidity of 50% and low relative wind velocities dominated by free convection processes.

The concept of an equivalent uniform temperature is quite useful because it enables one to assess thermal comfort levels in non-uniform environments in terms of a single thermal index, which can be directly related to subjective personal experience. Unlike the "operative temperature" defined in the ASHRAE handbook,[7] the equivalent uniform temperature is explicitly related to human thermal comfort and includes the effect of all latent heat loss phenomena on which that comfort depends.

6.2. Equivalent Uniform Temperatures in Passive Solar Heated Buildings.

In this section we present monthly histograms of the equivalent uniform temperature in two passive solar heated buildings located in Madison, Wisconsin. The histograms were calculated by PASOLE and SUNSPOT, the thermal network simulation codes. Double glazing with R5 night insulation is employed in both designs considered in this section, and the area/load ratio is held constant at 1.0 ft^2/(Btu/hr$^{\circ}$F). The allowable air temperature swing is from 63°F to 73°F. The Trombe wall design employs a 16 in. thick wall of high density concrete yielding 200 lbs of thermal storage mass per square foot of glazing. The direct gain system has 6 inches of concrete with a surface area equal to three times the glazing area, which yields 225 lbs/ft^2. Both configurations obtain an annual solar fraction of 50% in Madison. Equivalent uniform temperature histograms for the Trombe wall and direct gain buildings during the month of January are presented in Figs. 7 and 8 respectively.

Both buildings had a solar fraction of 35% for the month. The low solar fraction results from the high heating load in January. Since 65% of the heating load is met by the auxiliary heater, which is controlled by a thermostat set at 63°F, the air temperature is held at 63°F most of the time. The mean radiant temperature drops below the air temperature far enough to induce an equivalent uniform temperature which is between 60°F and 62°F over half the time. The Trombe wall building never falls any lower than the 60°F level. However, the direct gain building has a T_{eu}, which spends 10% of the time at the minimum level of 58°F to 60°F. Both buildings reach a maximum T_{eu} interval of 74°F to 76°F, although the time fractions at this level are quite small.

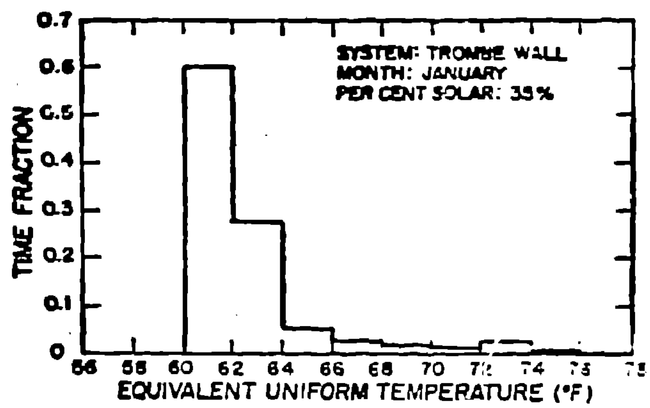

Fig. 7. Equivalent uniform temperature histogram for Trombe wall in January.

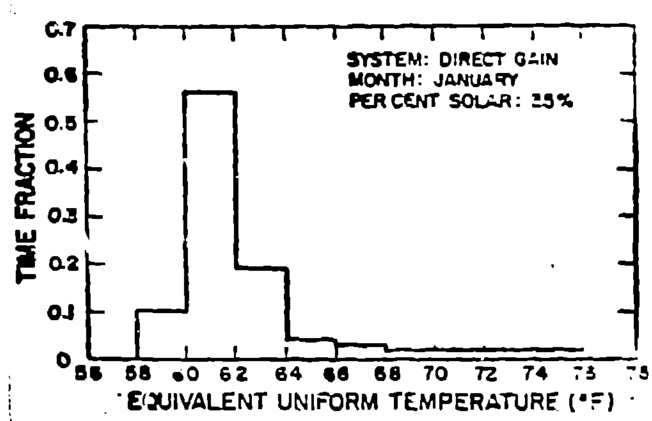

Fig. 8. Equivalent uniform temperature histogram for direct gain building in January.

In October the equivalent uniform temperature histograms have quite a different character as shown in Figs. 9 and 10. The largest time fraction is again in the 60°F to 62°F for both buildings due to the combined effect of the air temperature being thermostatically held to a minimum of 63°F and the thermal storage mass being cooler than the air when auxiliary heat is required. The effect of employing ventilation cooling wherever the air temperature gets up to 73°F is evident in that both buildings have the next largest T_{eu} time fraction in the 72°F to 74°F range. Due to radiation from the inner wall surface, the Trombe wall building reaches a maximum T_{eu} interval of 74°F to 76°F. Due to the combined effect of radiation from the thermal storage mass and direct irradiation by the solar source, the direct gain building reaches a maximum T_{eu} interval of 76°F to 78°F. The monthly solar fractions in October were 73% for the Trombe wall and 72% for the direct gain building. Increases in monthly solar fractions are always accompanied by T_{eu} histograms, which shift from the low end of the scale near the minimum air temperature toward the high end near the maximum air temperature. The mean radiant temperature range is usually much larger than the air temperature range which leads to T_{eu} histograms, which extend beyond the air temperature boundaries at both ends. Trombe walls always yield smaller T_{eu} swings than direct gain buildings, which generate comparable solar fractions.

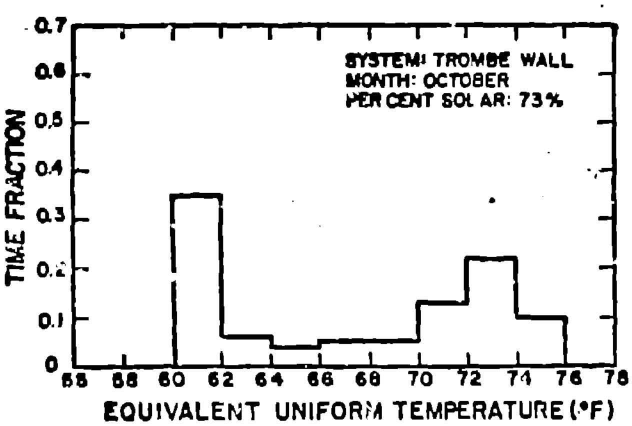

Fig. 9. Equivalent uniform temperature histogram for Trombe wall in October.

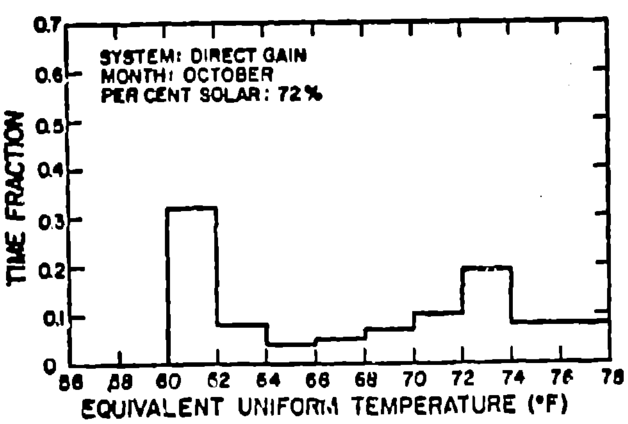

Fig. 10. Equivalent uniform temperature histogram for direct gain building in October.

As the above observations indicate, the problem of assessing comfort levels in passive solar heated buildings can be quite complex. Each particular building design in a given location will exhibit diurnal fluctuations in the equivalent uniform temperature, which are characteristic of that particular structure's response to the local climate. Each month there is a significant change in the character of the diurnal fluctuations as the structure responds to seasonal variations in heating load, total insolation and solar declination. Using thermal network codes, one can easily generate more data on thermal comfort indices than he has time to interpret. It is desirable to define an overall thermal quality index, which could serve as a basis for rating the comfort characteristics of different types of passive solar buildings on a comparative basis. Future work on thermal comfort at LASL will consider appropriate definitions for such an index.

7. CONCLUSIONS

Trombe wall and direct gain buildings each have certain advantages with respect to energy efficient performance. As a general rule, Trombe walls are able to achieve higher solar fractions on a limited amount of thermal storage mass. For thermal storage masses up to about 175 lbs per square foot of glazing Trombe walls consistently out perform direct gain buildings. However, if one is allowed to include more than about 175 lbs/ft_g^2 of thermal storage mass, the direct gain building begins to surpass the Trombe wall. This transition occurs because a Trombe wall reaches a performance peak between 150 lbs/ft_g^2 and 200 lbs/ft_g^2 (or 12 in. to 16 in. of 150 lb/ft^3 high density concrete) while performance of the direct gain building continues to rise as the surface area of the thermal storage mass is increased with the thickness held constant. Mixed systems offer potential advantages over either pure direct gain or Trombe wall approaches.

With respect to thermal comfort, the Trombe wall appears to be superior to direct gain buildings yieldling comparable solar fractions. Although both types of structures undergo equivalent uniform temperature swings, which exceed the thermostatically imposed air temperature boundaries at the upper and lower limits, the T_{eu} range in Trombe wall systems is consistently smaller than in direct gain buildings.

ACKNOWLEDGMENT

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